Field Tests of the Soil Heat Flux Plate Method and Some Alternatives

Tyson E. Ochsner,* Thomas J. Sauer, and Robert Horton

ABSTRACT

Heat flux plates are commonly used to measure soil heat flux, a component of the surface energy balance. The plate method is simple and precise, but several previous studies have demonstrated the potential for relatively large errors. Here we present the results of in situ tests of the plate method, and we describe some promising alternative methods. Summertime soil heat flux was measured with heat flux plates and with two alternative methods at each of three sites. In total, three alternative methods were used: a single probe gradient method, a three needle gradient method, and a self-calibrating plate method. The standard plate method underestimated the magnitude of the heat flux by 18 to 66% depending on the site and type of plate. Agreement between the alternative methods was good with discrepancies ranging from 2 to 6%. The plates underestimate flux apparently due to a combination of low plate thermal conductivity, thermal contact resistance, and latent heat transfer effects. The three needle gradient method for measuring heat flux performed well at all three sites, providing a good alternative to the standard plate method. The self-calibrating plate method performed well at the one site where it was tested and may also be a good alternative. Increased adoption of these methods should lead to more accurate soil heat flux and surface energy balance data.

S‍CIENTISTS in the disciplines of agronomy, forestry, ecology, and climatology often rely on surface energy balance measurements. These measurements help researchers quantify the transfers of water, energy, and trace gases at the earth's surface. Energy balance studies require, among other things, estimates of the heat flux at the soil surface. However, heat flux measurements cannot generally be obtained directly at the soil surface. Instead, the heat flux at some reference depth (G_r) is typically measured. Then, the flux at the surface is calculated by summing the reference soil heat flux and the rate of change of heat storage above the reference depth (Ochsner et al., 2006). Accurate determination of the heat flux at the soil surface, and hence accurate energy balance data, depend on accurate measurements of the reference soil heat flux.

The heat flux plate method is currently the most commonly used method for measuring soil heat flux. Heat flux plates are typically small, rigid, wafer-shaped sensors that are inserted into the soil horizontally at the reference depth (Sauer, 2002). An encapsulated thermopile in the plate produces a voltage proportional to the vertical temperature gradient across the plate. The thermal conductivity of the plate is fixed, and the heat flux through the plate is proportional to the temperature gradient. A calibration constant is used to convert the thermopile voltage output to a measure of the flux through the plate. The heat flux through the plate should be proportional to the conductive heat flux through the surrounding soil.

This method is relatively simple both conceptually and in practice. The plates are durable enough for long-term field use and can withstand repeated installation and excavation. With modern data logging equipment, the signal from heat flux plates can be measured with high frequency and precision for extended periods of time.

Four types of potential errors in the heat flux plate method are recognized. First, divergence or convergence of heat flow may be induced by differences between the plate thermal conductivity and the variable thermal conductivity of the soil (Philip, 1961). Second, divergence of heat flow may be caused by thermal contact resistance at the plate-soil interface (Fuchs and Hadas, 1973). Third, the plate may alter the heat flow in the surrounding soil indirectly by blocking liquid and vapor water movement (Sauer, 2002). And fourth, energy consumed or released by phase changes of water within the soil may not be properly measured (Mayocchi and Bristow, 1995).

Previous evaluations of the heat flux plate method have shown mixed results. Fuchs and Tanner (1967) reported good performance of heat flux plates in the field. Their heat flux plates had aluminum exteriors and glass interiors to maximize thermal conductivity and minimize contact resistance. Measurements of the flux through the plates and the thermal gradient in the surrounding soil were used to estimate the soil thermal conductivity, and this value agreed well with previously reported values for a similar medium. Fuchs and Hadas (1973) compared the performance of the aluminum and glass plates with that of commercially available plates with lower thermal conductivity. Laboratory tests in air-dry soils indicated that the aluminum and glass plates were accurate to within 7% but that the commercial plates underestimated flux by 35%. In the field, the aluminum and glass plates were accurate to within 3%, while the commercial plates underestimated heat flux by 47%. They concluded that high thermal conductivity plates are more accurate in all conditions than low thermal conductivity plates and that contact resistance is the most serious source of error when using heat flux plates. van Loon et al. (1998) performed laboratory tests on five commercially available heat flux sensors and reported average relative errors ranging from 4 to 20%. Sauer et al. (2003) also tested a variety of commercially available heat flux plates and found that the plates underestimated flux by 2 to 38% in dry sand and 13 to 73% in saturated sand. In moist clay-textured soil in the field, the plate performance ranged from a slight overestimate to a 71% underestimate.

T.E. Ochsner, Soil & Water Management Research Unit, Agricultural Research Service, St. Paul, MN 55108; T.J. Sauer, National Soil Tilth Laboratory, Agricultural Research Service, Ames, IA 50011; and R. Horton, Dep. of Agronomy, Iowa State Univ., Ames, IA 50011. Supported in part by the Iowa State University Agronomy Dep. Endowment Funds. Received 29 Aug. 2005. *Corresponding author (ochsner@umn.edu).

Surface energy balance studies play an increasingly important role in the earth and environmental sciences. These studies typically rely on the heat flux plate method for measuring soil heat flux, but, as indicated above, previous evaluations of the method indicate the potential for relatively large errors. The primary objective of this work is to provide a thorough in situ evaluation of the heat flux plate method using a variety of independent measurements for comparison. We hope to identify (i) the extent of errors in the plate method, (ii) the likely causes of these errors, and (iii) some promising alternatives to the plate method.

MATERIALS AND METHODS

Field Sites

We measured and recorded summertime soil heat flux under a bare soil surface in 2001, a corn (*Zea mays* L.) canopy in 2002, and a soybean [*Glycine max* (L.) Merr.] canopy in 2004. At the bare soil site, we measured heat flux 6 cm below the soil surface. The site was located a few kilometers northwest of Ames, IA. The soils at the site belong to the Canisteo-Clarion-Nicollet association (Typic Haplaquolls–Typic Hapludolls–Aquic Hapludolls). The soil texture was classified as clay according to the USDA classification scheme. Some basic soil physical properties for this site, as well as the other two, are presented in Table 1. Measurements began on 3 July 2001 and continued until 9 Aug. 2001. Sauer et al. (2003) presented results for 1 d of measurements at the bare soil site. This paper presents the complete results for that site.

We also measured heat flux at 6 cm below the soil surface at the corn site. The field was located a few kilometers south of Kelley, IA. The soils at the site belong to the Clarion-Nicollet-Webster association (Typic Hapludolls–Aquic Hapludolls–Typic Haplaquolls). The soil textural classification was sandy clay loam. Corn was planted in east-west rows with 76-cm row spacing. Measurements began on 18 June 2002 and continued until 14 Aug. 2002.

Finally, we measured heat flux 10 cm below the soil surface in a soybean field at the University of Minnesota Rosemount Research Center. The soil at the site is Waukegan silt loam (fine-silty over sandy or sandy-skeletal, mixed, superactive, mesic Typic Hapludolls). The soybean was planted in east-west rows with 76-cm row spacing. A cover crop of winter rye (*Secale cereale* L.) preceded the soybean, and the rye residue provided nearly complete ground cover throughout the measurement period, which began on 25 June 2004 and continued until 2 Oct. 2004.

Implementation of the Standard Heat Flux Plate Method

At the bare soil site, pairs of four types of heat flux plates were used (Table 2). These plates differed in size, shape, and composition (Sauer et al., 2003). The plates were installed in random order at 20-cm spacing along a north-south transect. At the corn site, a pair of the HFT1.1 plates was installed near

Table 1. Particle size distribution, organic matter content, and bulk density for the soils from the three field sites.

Site	Particle size			Organic matter content	Bulk density
	Sand	Silt	Clay		
	%			g kg^{-1}	Mg m^{-3}
Bare soil	32	25	43	65	1.13
Corn	45	23	32	54	1.14
Soybean	24	57	19	48	1.33

Table 2. Sensors used at each site and thermal conductivity values for the heat flux plates (λ_p).

Sensor†	λ_p	Sensors per site		
		Bare soil	Corn	Soybean
	W m^{-1} K^{-1}			
Standard plates				
610‡	0.21	2	–	–
CN3§	0.60	2	–	–
GHT1-C¶	0.63	2	–	–
HFT1.1#	1.26	2	2	3
Alternatives				
Three needle gradient	–	2	2	3
Single probe gradient	–	1	2	–
HFP01SC	–	–	–	3

† Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the USDA.
‡ C.W. Thornthwaite Associates, Pittsgrove, NJ.
§ Carter-Scott Manufacturing Pty. Ltd. Brunswick, Victoria, Australia.
¶ International Thermal Instrument Co., Del Mar, CA.
# Radiation and Energy Balance Systems, Seattle, WA.

the center of an interrow area. At the soybean site three HFT1.1 plates were used. These were installed at regular intervals across the interrow. Plate installation was accomplished by excavating a shallow trench, creating a slit in one sidewall just smaller than the plate dimensions, inserting the plate into the slit, and then backfilling the trench. The millivolt signals from the heat flux plates were measured using a data logger (CR21X at bare soil site and corn site, CR10X at soybean site, Campbell Scientific, Logan, UT) and converted to flux estimates using the plate manufacturers' calibrations.

Implementation of the Alternative Methods

Three alternative methods were used to obtain independent soil heat flux measurements. The three approaches used were a gradient method that relied on the single heat probe technique for determining thermal conductivity, a separate gradient method based on a three needle heat pulse sensor, and a self-calibrating plate method. At each site two of the independent approaches were used simultaneously in addition to the standard plate method (Table 2). A description of each method is presented below.

Single Probe Gradient Method

In this method, single heat probe sensors were used to measure the soil thermal conductivity (Bristow, 2002). Single probe sensors (TC1, SoilTronics, Burlington, WA) were installed horizontally adjacent to the heat flux plates. One sensor was used at the bare soil site and two at the corn site. These sensors were 14.5-cm long and 0.13-cm diam. stainless steel needles containing electrical resistance heaters and copper-constantan thermocouples. Probe temperature was monitored during 60 s of heating and for 60 s after heating. Ambient temperature drift rates were measured and subtracted from the temperature rise data (Jury and Bellantuoni, 1976). Estimates of thermal conductivity were obtained from the slope of the measured temperature rise vs. the natural logarithm of time. Thermal conductivity estimates from the heating and cooling periods were averaged. Copper-constantan thermocouples were installed 2 cm above and below each sensor to determine the temperature gradient. Flux was calculated by Fourier's Law.

Three Needle Gradient Method

In this method, three needle heat pulse sensors were used to measure both thermal conductivity and temperature gradient.

The sensors were installed horizontally adjacent to the heat flux plates. The sensor needles were parallel stainless steel tubes 4-cm long and 0.13 cm in diameter with 0.6-cm spacing. Each sensor was installed so that all three needles lay in a vertical plane. A brief (8–15 s) heat pulse was generated by applying 12 V to the heating element in the center needle, and the temperature increases were monitored using thermocouples encapsulated in the outer needles. Ambient temperature drift rates were measured and subtracted from the temperature rise data. The maximum temperature increase and the time of the maximum temperature increase were recorded for the outer needles. These two parameters were used to determine the soil thermal diffusivity and the soil volumetric heat capacity. Thermal conductivity was calculated as the product of the diffusivity and the heat capacity. The temperature gradient was calculated by dividing the difference in ambient temperatures between the two outer needles by the sum of the calibrated needle spacings. The needle spacings were calibrated in agar-stabilized water (Ochsner et al., 2003). Flux was calculated by Fourier's Law.

We used two different approaches for calculating the thermal properties. The method of Bristow et al. (1994) was used at the bare soil and corn sites. This method requires evaluation of the exponential integral to estimate volumetric heat capacity on which the thermal conductivity value depends. The complexity of the calculation necessitated post-processing of the data to determine thermal properties and heat flux. This post-processing can become cumbersome and time consuming for large data sets. We used an improved approach at the soybean site. We calculated thermal diffusivity using the method of Bristow et al. (1994), but we calculated volumetric heat capacity following the approach of Knight and Kluitenberg (2004). This calculation involves only a telescoped polynomial and was easily performed onboard the data logger, saving time and reducing the opportunity for post-processing mistakes. The thermal conductivity and heat flux were then calculated in real time.

In the three needle gradient method, the precision of the thermal conductivity measurement is primarily controlled by the precision with which the time to the maximum temperature rise is determined (Kluitenberg et al., 1995). The uncertainty in the time to maximum is no less than the interval between temperature rise measurements. At the bare soil and corn sites, we used a sampling frequency of 1 Hz, and thermal conductivity was resolved to within ± 0.09 W m^{-1} K^{-1} on average. At the soybean site the sampling frequency was increased to 4 Hz, and the resolution improved to ± 0.05 W m^{-1} K^{-1} on average. The sampling frequency is limited primarily by the configuration of the data acquisition system, but a frequency of 4 Hz should be achievable in many instances. The precision of the thermal conductivity estimate is secondarily determined by the precision in determining the maximum temperature rise. With the thermocouples and data loggers that we used, the maximum resolution of the temperature rise measurement was $\pm 0.006°$C. At the soybean site, we used the Savitzky and Golay (1964) smoothing algorithm suggested by Ham (J.M. Ham, personal communication, 2004) to improve the resolution. This is particularly helpful for determining soil volumetric heat capacity, the precision of which depends primarily on the temperature rise measurement.

Self-Calibrating Plate Method

This method is a relatively new variant of the flux plate method. We installed three HFP01SC self-calibrating heat flux plates (Hukseflux, Delft, the Netherlands) at the soybean site. This type of plate is 80 mm in diameter and 5-mm thick and has a film resistor (approximately 100 ohms) covering its upper face. Flux estimates were obtained by dividing the millivolt out-

put signal from the plate by the in situ calibration constant. The calibration constant was adjusted every 3 h. To calculate the calibration constant, a 180 s heat pulse was generated by applying 12 V to the film resistor. The plate response to the self-heating (V_a) was quantified by

$$V_a = V_s(180) - [V_s(0) + V_s(360)]/2 \qquad [1]$$

where $V_s(i)$ is the millivolt output from the plate i seconds after the initiation of the heat pulse. The heat pulse creates a heat flux through the plate which is in addition to the "ambient" heat flux through the plate driven by the ambient soil temperature gradient. Thus, the last term in Eq. [1] subtracts the output signal due to the "ambient" flux, leaving the output signal attributable to the self-heating. The in situ calibration factor (E, mV m^2 W^{-1}) for the plate was then estimated as V_a divided by one-half the heating power per unit area:

$$E = 2V_a[(R_r^2 A_s)/(V_r^2 R_s)] \qquad [2]$$

where R_r is the resistance of a current-sensing resistor in series with the film resistor, V_r is the voltage drop across the current-sensing resistor, A_s is the surface area of the plate (3.89×10^{-3} m^2), and R_s is the resistance of the film resistor (Hukseflux Thermal Sensors, 2003). We are unaware of any publications that provide a theoretical basis for this self-calibration procedure. Interested readers can refer to the Appendix for one approach to deriving Eq. [2].

RESULTS

Time Series of Soil Heat Flux

To facilitate direct comparisons between methods, we express the results in terms of the heat flux at the reference depth as opposed to the heat flux at the soil surface. At the bare soil site heat flux at 6 cm ranged from about -50 to 150 W m^{-2} (Fig. 1a). Daily maximum values typically occurred between 1100 and 1400 h, and daily minimums typically occurred between 2300 and 0400 h. The three needle gradient method consistently measured fluxes of higher magnitude than those reported by the heat flux plates. The single probe gradient method likewise resulted in larger heat flux estimates than the plates (data not shown). On Days 209 and 210, the three needle gradient method reported maximum fluxes more than 100 W m^{-2} greater than those measured by the 610 plates. Between the various types of plates, we observed considerable variation in performance. The HFT1.1 plates reported the highest magnitude of soil heat flux and the 610 plates reported the lowest magnitude. The values of heat flux measured by the other two types of plates were intermediate (data not shown).

Cumulative values of heat flux for the bare soil site are plotted in Fig. 1b. Over a 3-wk period the cumulative flux measured by the three needle gradient method reached 23.3 MJ m^{-2}. The HFT1.1 plates reported a slightly lower cumulative flux of 21.6 MJ m^{-2}. In contrast, the 610 plates reported a much lower cumulative heat flux of 9.8 MJ m^{-2}. Again, the other two types of heat flux plates yielded data that were intermediate (data not shown). Figure 1b shows that differences between the methods for measuring heat flux do not necessarily cancel out over the course of a diurnal cycle, rather they can accumulate over time.
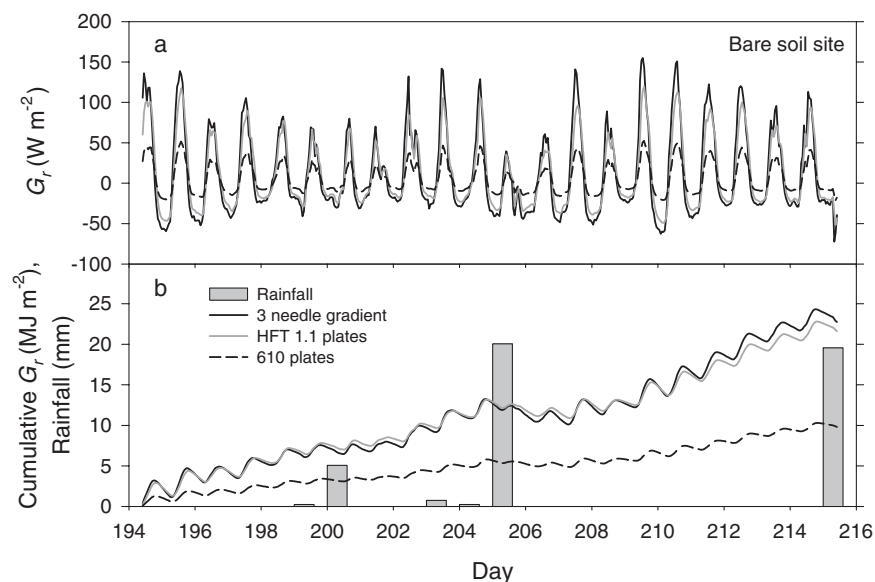
Fig. 1. Time series of (a) soil heat flux at the reference depth (G_r) and (b) cumulative G_r at the bare soil site as measured by the three needle gradient method, the HFT1.1 plates, and the 610 plates.

Under the closed vegetative canopy at the corn site, heat flux at the 6-cm depth typically ranged from -40 to 70 W m^{-2} (Fig. 2a). Daily maximum values occurred between 1100 and 1500 h, and daily minimums occurred between 2400 and 0600 h. Again, the gradient methods consistently measured fluxes of higher magnitude than those reported by the heat flux plates. The three needle gradient method reported daily maximum fluxes typically 15 to 25 W m^{-2} greater than those measured by the HFT1.1 plates. Meanwhile, the three needle and single probe gradient methods were in close agreement.

Cumulative values of soil heat flux for the corn site are plotted in Fig. 2b. Seventy millimeters of rain fell on Day 191, and heat flux was negative (i.e., upward) for

about 36 consecutive hours thereafter. During this period the difference in cumulative heat flux between the plate method and the three needle gradient method reached 1.09 MJ m^{-2} or 63%.

At the soybean site, heat flux at the 10-cm depth ranged from -30 to 65 W m^{-2} (Fig. 3a). Daily maximum values occurred between 1300 and 1600 h, and daily minimums occurred between 0100 and 0700 h. As at the other two sites, the three needle gradient method consistently measured fluxes of higher magnitude than those reported by the heat flux plates. The self-calibrating plate method did likewise. The three needle gradient method reported daily maximum fluxes 25% greater on average than those measured by the HFT1.1 plates. Meanwhile, the average difference between daily maximum fluxes from the
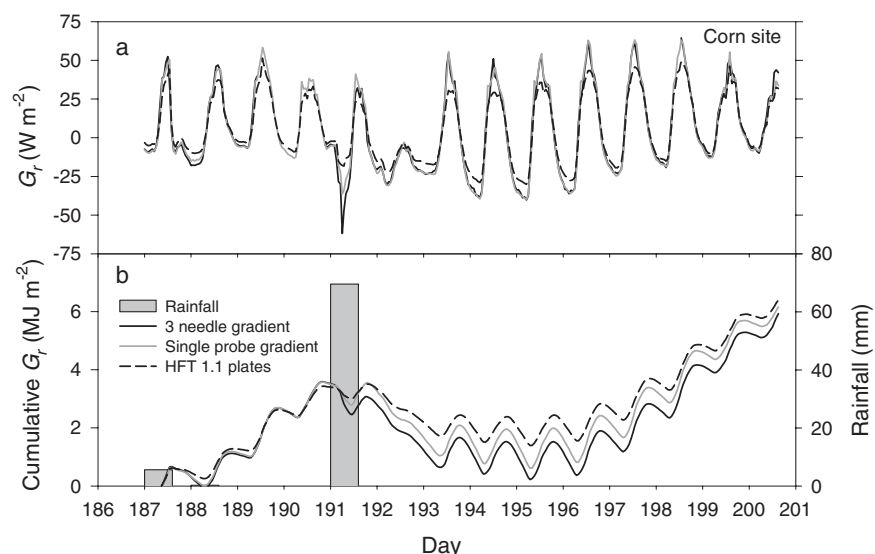
Fig. 2. Time series of (a) G_r and (b) cumulative G_r at the corn site as measured by the three needle gradient method, the single probe gradient method, and the HFT1.1 plates.
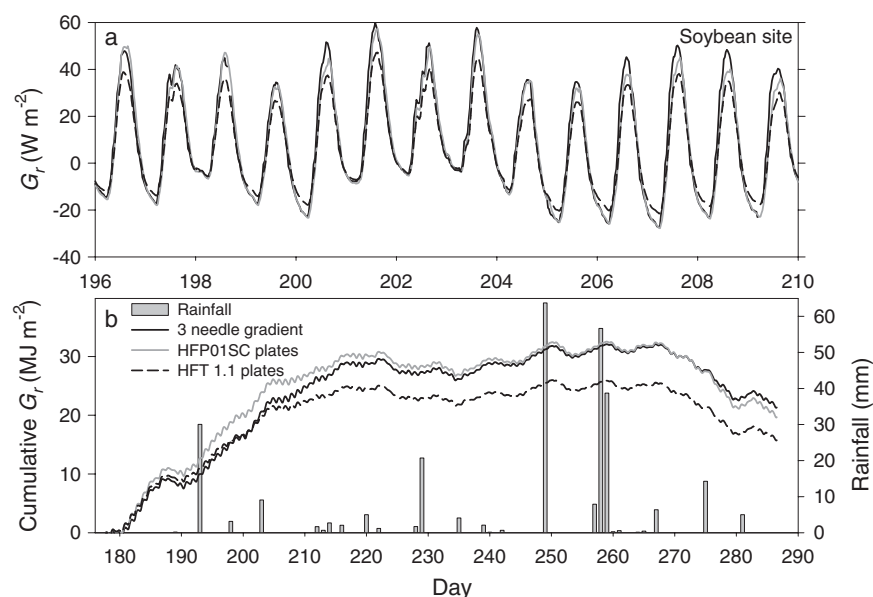
Fig. 3. Time series of (a) G_r and (b) cumulative G_r at the soybean site as measured by the three needle gradient method, the HFT1.1 plates, and the HFP01SC plates. Note that for the sake of clarity (a) contains only a small portion of the data in (b).

three needle gradient method and the self-calibrating plate method was −1%.

Cumulative values of soil heat flux for the soybean site are plotted in Fig. 3b. Cumulative heat flux during the study period reached a maximum of 32 MJ m^{-2} on Day 266 according to the three needle gradient method and the self-calibrating plate method. In contrast, the

HFT1.1 plates reported on Day 266 a cumulative heat flux of 26 MJ m^{-2}, 19% lower.

One-to-One Comparison of Methods

One-to-one plots of the heat flux data (Fig. 4–6) and linear regression statistics (Table 3) highlight the differ-
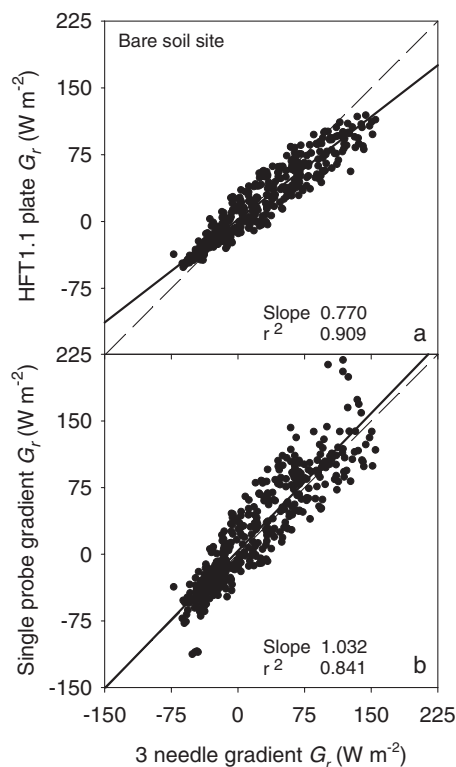

Fig. 4. One-to-one comparison of G_r at the bare soil site as measured by (a) the HFT1.1 plates and (b) the single probe gradient method vs. the three needle gradient method. The solid lines are the regression lines, and the dashed lines are the one-to-one lines.
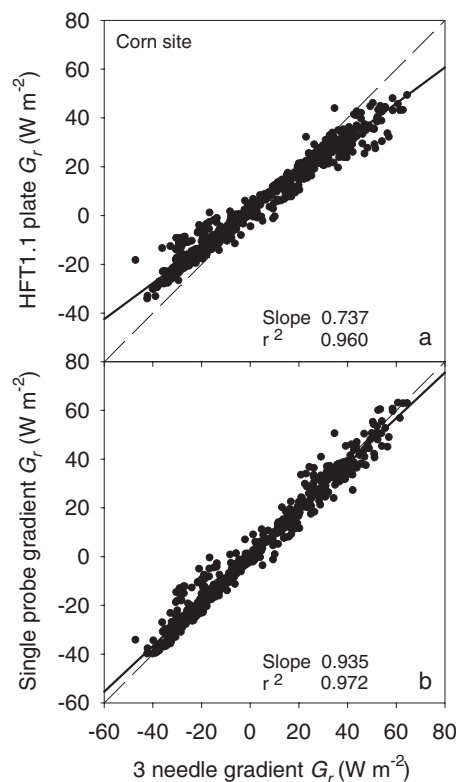

Fig. 5. One-to-one comparison of G_r at the corn site as measured by (a) the HFT1.1 plates and (b) the single probe gradient method vs. the three needle gradient method. The solid lines are the regression lines, and the dashed lines are the one-to-one lines.
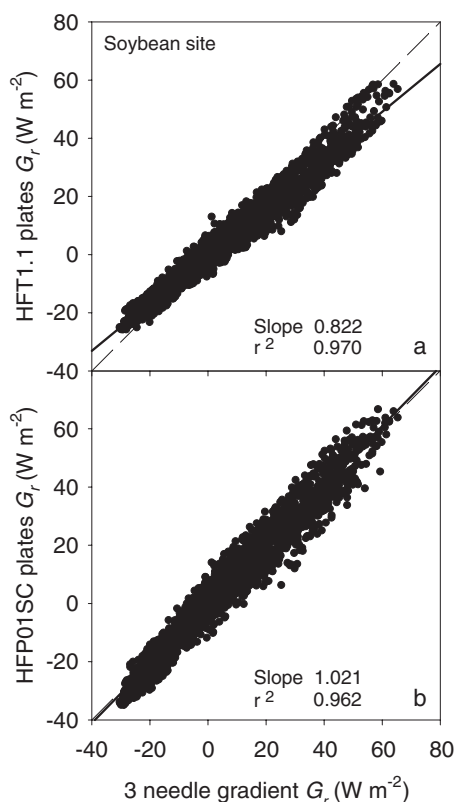
the comparison between the gradient methods yields a slope of 0.935 (Fig. 5b). The trend continues at the soybean site where the linear regression between the HFT1.1 plates vs. the three needle gradient method produced a slope of 0.822 (Fig. 6a). Meanwhile, the regression slope for the self-calibrating plate method vs. the three needle gradient method gives a slope of 1.02 (Fig. 6b). At all three sites the standard heat flux plates underestimated the soil heat flux relative to the alternative methods, and the alternative methods were in good agreement with each other.

Variability of Heat Flux Estimates

For each site we calculated the mean of the midday range of heat flux estimates across replicates of each sensor type (Table 4). These data provide a quantitative way to compare variability across methods and sensors. At the bare soil site the mean midday range for the four types of plates used increased as the plate thermal conductivity increased. One source of plate to plate variability is poor plate-soil contact. Poor contact may cause less variability for plates with low thermal conductivities, that is plates which already significantly restrict heat flow. Across all three sites, the average midday range for the HFT1.1 sensors was 26 W m^{-2}, while for the three needle gradient method it was 13 W m^{-2}. Both of these ranges are well within reported ranges of spatial variability of soil heat flux (Ham and Kluitenberg, 1993; Kustas et al., 2000).

DISCUSSION

Summary of Errors in the Plate Method

The results were consistent across three sites in three different years: the heat flux plates gave flux estimates of lower magnitude than those from the alternative methods. To aid in interpreting these results, consider the context. Under controlled laboratory conditions with known fluxes, heat flux plates have been shown to underestimate flux from 2 to 73% (Sauer et al., 2003). And, equally large underestimates have been reported in the field (Fuchs and Hadas, 1973; Sauer et al., 2003). In our field experiments heat flux plates underestimated the magnitude of the soil heat flux by 18 to 66% relative to the three needle gradient method. Meanwhile, the three needle gradient method exhibited excellent agreement with the single probe gradient method and the self-

Fig. 6. One-to-one comparison of G_r at the soybean site as measured by (a) the HFT 1.1 plates and (b) the HFP01SC plates vs. the three needle gradient method. The solid lines are the regression lines, and the dashed lines are the one-to-one lines.

ences between these methods. For the bare soil site, linear regression of data from the HFT1.1 plates versus data from the three needle gradient method yields a slope of 0.770 (Fig. 4a). The magnitude of flux measured by the HFT1.1 plates is about 23% lower than that measured by the three needle gradient method. The underestimations are greater for the other types of heat flux plates: 66% for the 610 plates, 34% for the CN3 plates, and 47% for the GHT-1C plates. In contrast, linear regression of data from the single probe gradient method versus data from the three needle gradient method yields a slope of 1.03 (Fig. 4b).

A similar pattern exists in the data from the corn site. There the slope of the linear regression between data from the HFT1.1 plates vs. data from the three needle gradient method yields a slope of 0.737 (Fig. 5a), while

Table 3. Linear regression statistics and mean absolute difference for G_r values measured by heat flux plates vs. G_r values measured with the three needle gradient method.

Plate	Slope	Intercept	r^2	Mean absolute difference
		W m^{-2}		W m^{-2}
Bare soil site				
610	0.337	1.18	0.913	28.2
CN3	0.657	1.80	0.913	16.4
GHT-1C	0.535	3.47	0.853	21.8
HFT1.1	0.770	2.25	0.909	13.4
Corn site				
HFT1.1	0.737	1.73	0.960	6.17
Soybean site				
HFT1.1	0.822	−0.221	0.970	2.79

Table 4. Mean midday range of G_r across replicates of the same sensor type.

	Site		
Sensor	Bare soil	Corn	Soybean
	W m^{-2}		
Standard plates			
610	0.9	–	–
CN3	7	–	–
GHT1-C	30	–	–
HFT1.1	59	10	8
Alternatives			
Three needle gradient	10	16	13
Single probe gradient	–	22	–
HFP01SC	–	–	12

calibrating plate method. It is conceivable that these three independent alternative methods were all overestimating the heat flux by nearly identical amounts, but the probability of such an occurrence appears remote. More likely, especially in light of previous studies, is the simple explanation that heat flux plates underestimate soil heat flux.

The HFT1.1 plates gave larger flux values than the other three types of plates we tested, so Fig. 4 through 6 represent the "best case" scenario for the plates we evaluated. The degree of flux underestimation at the bare soil site followed the order: HFT1.1 plates < CN3 plates < GHT-1C plates < 610 plates. This is consistent with the order of underestimation previously observed in the laboratory: HFT1.1 plates < CN3 plates ≈ GHT-1C plates < 610 plates (Sauer et al., 2003). The data suggest that one should generally expect to underestimate soil heat flux by more than 25% with these other three types of plates.

Causes of Errors in the Plate Method

Differences between Plate and Soil Thermal Conductivities

Heat flow divergence induced by differences between plate and soil thermal conductivities is a well-known source of error in the plate method. In theory, this error can be corrected if both thermal conductivities and the plate dimensions are known (Philip, 1961). We applied this correction to the data from the heat flux plates to estimate the effect of divergence. For soil thermal conductivity we used the values measured by the three needle sensors, and we measured the plate dimensions and thermal conductivity in the laboratory (Sauer et al., 2006). Statistics resulting from linear regression of this corrected data from the heat flux plates vs. the data from the three needle gradient method are given in Table 5.

For the 610, CN3, and GHT-1C plates, the regression slopes increased relative to the uncorrected data, and the increases were statistically significant ($P < 0.05$, based on the 95% confidence intervals for the regression slopes). No significant changes in the regression slopes for the HFT1.1 plates were observed. The thermal conductivity of the HFT1.1 plates is much higher than that of the other plates, so heat flow divergence is less with the HFT1.1 plates. The regression slopes at the bare soil site for the 610, CN3, and HFT1.1 plates are not significantly different from each other ($P < 0.05$) following the Philip

(1961) correction. This consistency of performance is only achieved by using measured values for plate thermal conductivity and dimensions. The effects of the correction are inconsistent if manufacturer's values for these parameters are used (Sauer et al., 2003; van Loon et al., 1998).

The Philip (1961) correction increased the magnitude of the heat flux estimates by 12 to 126% for the three types of plates with relatively low conductivity. This demonstrates that plates with thermal conductivities <1 W m^{-1} K^{-1} are susceptible to large heat flow divergence errors which cause underestimation of the magnitude of soil heat flux. To remove these errors, soil thermal conductivity data are required. In many applications these data are not available, and it is not possible to apply the Philip (1961) correction. When soil thermal conductivity data are available, heat flux plates are unnecessary, since the flux can be calculated from simple measurements of the corresponding soil temperature gradient.

Thermal Contact Resistance

Thermal contact resistance at the plate-soil interface is a second potential cause of heat flow divergence. The CN3 and GHT-1C plates both have metal exteriors, while the HFT1.1 plates and 610 plates have plastic exteriors. As noted by Fuchs and Hadas (1973), plates with metal exteriors have reduced thermal contact resistance. However, in our study the plates with metal exteriors did not outperform the plastic coated HFT1.1 plates, even after the Philip (1961) correction. This suggests that thermal contact resistance was not a dominant error source for the plates in the fine-textured soil at the bare soil site.

Water Flow Disruption

Heat flux plates are impervious and block the movement of soil water in both the liquid and vapor phases. This disruption may alter the soil thermal properties, which in turn may affect soil temperature and heat flux. We performed a simple experiment at the soybean site to measure the distortion of soil water content caused by impervious disks. We buried 30 high density polyethylene disks in the soil at 2- and 10-cm depths. The disks were the diameter and thickness of HFP01SC self-calibrating heat flux plates, which are larger than many other commercially available plates. The disks were buried in the middle of the soybean interrow to minimize shading, and the residue was removed to expose a bare soil surface. Each day for 10 d following a rainfall event, soil temperature and water content were measured 1-cm above and below three of the disks at each depth. Temperature and water content were also measured at the same depths in the surrounding soil. Temperature was measured by inserting a needle containing a thermocouple into the soil at the depth of interest, and water content was measured by oven drying small soil samples from each depth.

The resulting data show the extent to which impervious plastic disks can distort soil water content distributions (Fig. 7a). A 30-mm rainfall event on Day 193 created a temporary uniform water content distribution around the disks buried at the 2-cm depth. However, the impervious disks caused the overlying soil to

Table 5. Linear regression statistics and mean absolute difference for G_r values measured by heat flux plates after applying the Philip (1961) corrections vs. G_r values measured with the three needle gradient method.

Plate	Slope	Intercept	r^2	Mean absolute difference
Bare soil site		W m^{-2}		W m^{-2}
610	0.761	2.79	0.912	13.8
CN3	0.789	2.23	0.913	12.9
GHT-1C	0.597	3.92	0.853	19.9
HFT1.1	0.750	2.22	0.909	13.9
Corn site				
HFT1.1	0.730	1.65	0.962	6.25
Soybean site				
HFT1.1	0.836	−0.219	0.966	2.70
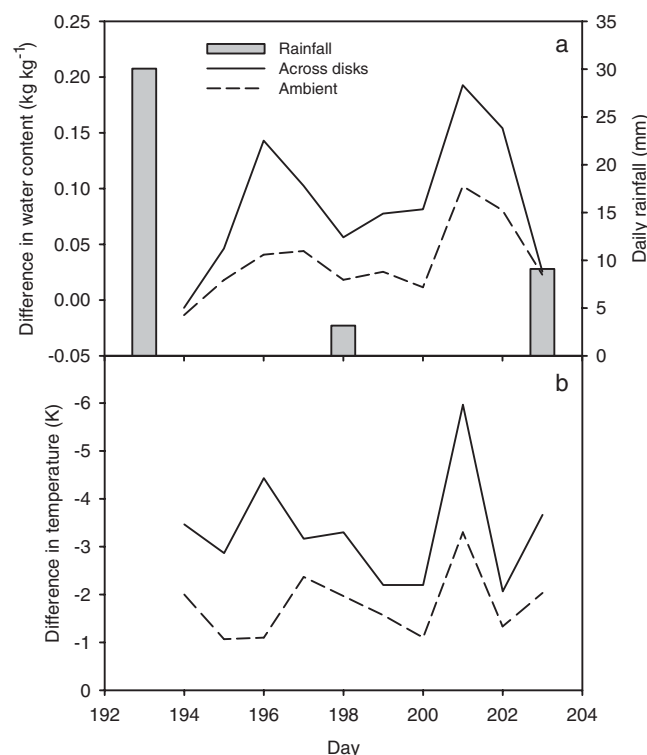
Fig. 7. Midday vertical (a) soil water content and (b) temperature differences across plastic disks (below–above) buried 2 cm beneath a bare soil surface. Ambient gradients as measured in the adjacent soil and daily rainfall totals are also shown.

dry more rapidly than the surrounding soil, leading to a much steeper water content gradient by Day 196. This gradient, two to three times steeper than in the surrounding soil, was sustained until the 10-mm rainfall event on Day 203. At the 10-cm depth, the disks also caused the water content gradients to be about twice as steep as in the surrounding soil (data not shown). Clearly, impervious plastic disks cause the overlying soil to dry out faster than the surrounding soil.

The soil temperature data show a similar disruption caused by the disks (Fig. 7b). The vertical soil temperature gradient across the disks was about twice as large as the gradient in the surrounding soil. The plastic disks reduced heat conduction causing a steeper gradient and elevated temperatures in the overlying soil. This thermal disruption was evident even when the water content distribution was uniform on Day 194. This suggests that the reduced heat transfer contributed to increased evaporation in the overlying soil thereby altering the soil water distribution. Distorted soil water distributions may then be primarily a symptom of, as opposed to a cause of, disrupted heat transfer.

Latent Heat Transfer Effects

If a portion of the downward heat flux measured at one depth by a heat flux sensor is consumed in evaporation at a deeper depth, and if the resulting water vapor subsequently is transferred upward out of the soil, a problem arises in the surface energy balance (Buchan, 1989; Mayocchi and Bristow, 1995). Aboveground sen-

sors (e.g., eddy covariance) would detect the vapor and count it as part of the latent heat flux, while the heat flux sensor counts the energy which produced the vapor as part of the soil heat flux. This is a double counting. If an objective of the study is to measure the total evapotranspiration from a given land area, then one should include all the evaporation from the soil regardless of the depth in the soil at which the phase change occurred. This would lead one to agree with the aboveground sensors and to deem the soil heat flux estimate too high. Unfortunately, this error is difficult to detect since the soil depth at which evaporation is occurring is generally unknown. All heat flux sensors are equally prone to this type of error if they are installed too close to the soil surface. Therefore, the discrepancy between the heat flux plates and the other methods used in this study are not caused by this type of error.

There is perhaps another means by which latent heat transfer causes errors in heat flux plate measurements. Heat flux plates are designed and calibrated to measure heat tranfer by conduction, but in moist soil latent heat transfer at the pore scale is virtually inseparable from conduction. We hypothesize that the standard plate method may underestimate the total heat flux in part because the method does not properly measure pore scale latent heat transfer. The data do provide some indirect evidence supporting this hypothesis. We know that latent heat transfer as a portion of the total heat flux decreases with depth. Westcot and Wierenga (1974) reported that vapor flux accounted for 15 to 40% of the total soil heat flux at the 5-cm depth in a fine sand and 17 to 34% at the 11-cm depth. In our study, the underestimation by the HFT1.1 plates was about 25% at 6 cm (bare soil and corn sites) and 18% at 10 cm (soybean site) according to the slopes in Table 3. The improved performance of the heat flux plates at the deeper depth is consistent with a reduction in latent heat transfer with depth.

Alternatives to the Plate Method

We now discuss some alternatives to heat flux plates, beginning with the single probe gradient method. Cobos and Baker (2003) used a similar method and reported good agreement with a known heat flux in the laboratory and with the self-calibrating plate method in the field. They concluded that the gradient method was a viable alternative to the heat flux plate method. Like them, we found agreement between the single probe gradient method and an independent flux measurement (the three needle gradient method in our case). However, in our study the precision of the single probe gradient method was often hindered by noisy thermal conductivity data. This noise seemed to arise from errors in the temperature measurements while the sensor's heater was active. The current flowing through the heater apparently affected the signal from the co-located thermocouple. This phenomenon occurred sporadically in five out of six sensors that we used. To avoid this problem, one could use only the temperature data collected after the heater is turned off or perhaps provide better electrical isolation between the thermocouple and heating

circuits. Due to the long measurement window (several minutes), ambient temperature drift is a definite concern with this method, but its effects can be minimized by employing a temperature drift correction procedure as we have done. Precise placement of the external thermocouples is also necessary to accurately measure the thermal gradient.

Of the methods we tested, the three needle gradient method may be the best alternative to heat flux plates. It offers a direct measurement of the soil thermal gradient and conductivity with the same sensor. The method performed well at all three of the sites in this study. With these sensors, measurements of soil volumetric heat capacity and thermal diffusivity are quite sensitive to needle deflection. However, the error analysis by Kluitenberg et al. (1995) showed that thermal conductivity measurements should be unaffected by needle deflection. Another attractive feature of the method is that soil temperature, thermal properties, heat storage, and soil water content (Heitman et al., 2003; Ochsner et al., 2003) can also be monitored with the same type of sensor.

The self-calibrating plate method also performed well at the one site where we used it. The user's manual states that the correction imposed by the procedure is "in the first approximation" equal to the heat flow divergence around the sensor. The factors influencing the accuracy of the approximation are not specified. Laboratory evaluations have produced mixed results. van Loon et al. (1998) found that the procedure was accurate to within 5%, but Cobos and Baker (2003) found that it overestimated flux by 22% in the laboratory. A presentation and evaluation of the theoretical basis for this method is needed. However, the procedure seems to be effective in situ. The primary disadvantage of this method is that the plate is relatively large. Therefore, it is difficult to install without disturbing the soil, and it will distort the water content and temperature of the overlying soil.

The three alternative methods described here require more measurement channels and more complex datalogger programming than does the standard heat flux plate method. The sensors for the single probe and three needle gradient methods are also somewhat more fragile than standard heat flux plates. And, commercial availability for the three needle heat pulse sensors is currently limited. These factors should all be considered, along with the superior accuracy of the alternative methods, when deciding how to measure soil heat flux.

CONCLUSION

The plate method has remained the dominant method of soil heat flux measurement for decades. The simplicity of the method is certainly attractive. However, data from this study and several previous studies show that heat flux plates underestimate soil heat flux. These underestimates likely arise from low plate thermal conductivities, thermal contact resistance, and latent heat transfer effects. The three needle gradient method demonstrated here is a viable successor to the plate method. The self-calibrating plate method also shows potential. Further testing of these alternatives is warranted to determine the extent of their

reliability and accuracy. Our results suggest that increased adoption of these methods should improve the accuracy of soil heat flux and surface energy balance data.

APPENDIX

Imagine a self-calibrating plate in perfect thermal contact with an infinite isothermal medium having thermal properties exactly matching the plate. When the heater on top of the plate is activated, half of the heat flux would pass upward into the surrounding medium and half would pass downward through the plate (ignoring edge effects). The heat flux through the plate for this idealized scenario would be one half of the heating power per unit area, $Q/2$. In reality, for a self-calibrating plate installed in soil, the actual flux through the plate caused by the heating, G_h, will generally not be equal to $Q/2$. The ratio of the ideal to the actual flux, $(Q/2)/G_h$, is a measure of the heat flow distortion during heating.

Now, consider the same plate installed in the same soil, but with the heater turned off. The heat flux measured by the plate, G_m, typically differs from the actual flux through the soil, G_r. The ratio of these two fluxes, G_r/G_m, is a measure of the heat flow distortion under ambient conditions. To derive Eq. [2], one can begin by assuming that the heat flow distortion under ambient conditions is equal to the heat flow distortion during heating.

$$G_r/G_m = (Q/2)/G_h \qquad [A1]$$

The goal of the self-calibration is to determine a calibration constant, E (mV m^2 W^{-1}), such that

$$E = V_s/G_r \qquad [A2]$$

where V_s is the millivolt signal from the plate under ambient conditions. Solving [A1] for G_r and substituting the resulting expression into [A2] gives

$$E = V_s \frac{G_h}{G_m(Q/2)} \qquad [A3]$$

Now, under ambient conditions V_s is given by

$$V_s = E_t G_m \qquad [A4]$$

where E_t is the true sensitivity of the thermopile and is independent of soil properties. The actual flux through the plate caused by turning on the heater is

$$G_h = V_a/E_t \qquad [A5]$$

where V_a is given by Eq. [1] in the Materials and Methods section. Inserting Eq. [A4] and [A5] into Eq. [A3] gives

$$E = 2V_a/Q \qquad [A6]$$

which is equivalent to Eq. [2] in the Materials and Methods section. The validity of Eq. [A6] depends primarily on the assumption required to formulate Eq. [A1], that is, that the heat flow distortion during heating is proportionally the same as the heat flow distortion under ambient conditions.

REFERENCES

Bristow, K.L. 2002. Thermal conductivity. p. 1209–1226. *In* J.H. Dane and G.C. Topp (ed.) Methods of soil analysis. Part 4. SSSA, Madison, WI.
Bristow, K.L., G.J. Kluitenberg, and R. Horton. 1994. Measurement of

soil thermal properties with a dual-probe heat-pulse technique. Soil Sci. Soc. Am. J. 58:1288–1294.

Buchan, G.D. 1989. Soil heat flux and soil surface energy balance: A clarification of concepts. p. 627–634. *In* Proc. 4th Australasian Conf. Heat Mass Transfer, Christchurch, New Zealand. 9–12 May 1989. Univ. of Canterbury, Christchurch, NZ.

Cobos, D.R., and J.M. Baker. 2003. In situ measurement of soil heat flux with the gradient method. Vadose Zone J. 2:589–594.

Fuchs, M., and A. Hadas. 1973. Analysis of the performance of an improved soil heat flux transducer. Soil Sci. Soc. Am. Proc. 37:173–175.

Fuchs, M., and C.B. Tanner. 1967. Calibration and field test of soil heat flux plates. Soil Sci. Soc. Am. Proc. 32:326–328.

Ham, J.M., and G.J. Kluitenberg. 1993. Positional variation in the soil energy balance beneath a row-crop canopy. Agric. For. Meteorol. 63:73–92.

Heitman, J.L., J.M. Basinger, G.J. Kluitenberg, J.M. Ham, J.M. Frank, and P.L. Barnes. 2003. Field evaluation of the dual-probe heat-pulse method for measuring soil water content. Vadose Zone J. 2:552–560.

Hukseflux Thermal Sensors. 2003. HFP01SC, Self calibrating heat flux sensor, heat transfer coefficient sensor: User manual version 0301. Hukseflux Thermal Sensors, Delft, the Netherlands.

Jury, W.A., and B. Bellantuoni. 1976. A background temperature correction for thermal conductivity probes. Soil Sci. Soc. Am. J. 40:608–610.

Kluitenberg, G.J., K.L. Bristow, and B.S. Das. 1995. Error analysis of heat pulse method for measuring soil heat capacity, diffusivity, and conductivity. Soil Sci. Soc. Am. J. 59:719–726.

Knight, J.H., and G.J. Kluitenberg. 2004. Simplified computational approach for dual-probe heat-pulse method. Soil Sci. Soc. Am. J. 68:447–449.

Kustas, W.P., J.H. Prueger, J.L. Hatfield, K. Ramalingam, and L.E. Hipps. 2000. Variability in soil heat flux from a mesquite dune site. Agric. For. Meteorol. 103:249–264.

Mayocchi, C.L., and K.L. Bristow. 1995. Soil surface heat flux: Some general questions and comments on measurments. Agric. For. Meteorol. 75:43–50.

Ochsner, T.E., R. Horton, and T. Ren. 2003. Use of the dual-probe heat-pulse technique to monitor soil water content in the vadose zone. Vadose Zone J. 2:572–579.

Ochsner, T.E., T.J. Sauer, and R. Horton. 2006. Soil heat storage measurements in energy balance studies. Agron J. 98 (in press).

Philip, J.R. 1961. The theory of heat flux meters. J. Geophys. Res. 66:571–579.

Sauer, T.J. 2002. Heat flux density. p. 1233–1248. *In* J.H. Dane and G.C. Topp (ed.) Methods of soil analysis. Part 4. SSSA, Madison, WI.

Sauer, T.J., D.W. Meek, T.E. Ochsner, A.R. Harris, and R. Horton. 2003. Errors in heat flux measurement by flux plates of contrasting design and thermal conductivity. Vadose Zone J. 2:580–588.

Sauer, T.J., T.E. Ochsner, and R. Horton. 2006. Soil heat flux plates: Heat flow distortion and thermal contact resistance. Agron. J. 98 (in press).

Savitzky, A., and M.J.E. Golay. 1964. Smoothing and differentiation of data by simplified least squares procedures. Anal. Chem. 36: 1627–1639.

van Loon, W.K.P., H.M.H. Bastings, and E.J. Moors. 1998. Calibration of soil heat flux sensors. Agric. For. Meteorol. 92:1–8.

Westcot, D.W., and P.J. Wierenga. 1974. Transfer of heat by conduction and vapor movement in a closed soil system. Soil Sci. Soc. Am. Proc. 38:9–14.